range of values to ease the circuit design and realization problem.

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Short Papers

Further Experiments Seeking Evidence of Nonthermal Biological Effects of Microwave Radiation

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***Abstract*—Carpenter and Livstone's [1] experiments on beetle pupae are repeated and extended. In the experiments conducted, increased incidence of abnormal development occurred due to exposure to microwave energy, both CW and pulsed. This effect was observed at the power level of 8.6 mW/cm². Measurements are reported which specify the microwave environment encountered by the insect.**

I. INTRODUCTION

This short paper reports experiments undertaken to verify and augment the observations of Carpenter and Livstone [1] on teratological damage inflicted upon the darkling bettle *Tenebrio molitor* by low power microwave irradiation.

We first repeated the Carpenter and Livstone study in waveguide at the 20-mW CW irradiation level with a much larger sample population and, having confirmed their results, conducted experiments in which individual experimental parameters—duty cycle, orientation, pupa age, power level, and total absorbed energy—were varied in a phenomenological approach to elucidate mechanisms by which teratological damage is realized. Finally, measurements were made to specify the microwave environment encountered by the insect.

II. EXPERIMENT

One- to two-day-old pupae (nominally, 3/16-in diameter × 5/8-in length) were mounted for irradiation in styrofoam blocks, then inserted along the center line of X-band waveguides with their anterior portions towards the power source as shown in Fig. 1 The waveguide was terminated in a matched load. The pupae were irradiated at 9 GHz, then placed for the duration of pupation in individual numbered vials in a darkened chamber at 21°C. The emergent adults were categorized for gross morphological defects as per the scheme of Carpenter and Livstone in ignorance of whether a particular insect was from the irradiated or control group ("single-blind").

No attempt was made to impedance match the pupa and holder, in contrast to the method of Carpenter and Livstone. The combined mismatch was considered small with less than 5.1 percent of the incident power being reflected (13-dB return loss). Also the introduction of a matching element would distort the field distribution in the vicinity of the pupa, thereby further complicating interpretation of field strength measurements.

Waveguide was chosen as the experimental environment to conform with the original experiments of Carpenter and Livstone, In addition, a waveguide apparatus allows the precise determination of incident and reflected power levels, and of the power absorbed by the specimen.

A diagram of the microwave circuit used for the simultaneous irradiation of four pupae is shown in Fig. 2. An 80-mW CW Gunn oscillator was the microwave source. The power incident on each pupa was 20 mW, which is equivalent to a power density of 17.1 mW/cm², at the center of the X-band waveguide. Free space radiation at a power density of 17.1 mW/cm² could be obtained using a 1-W source and a horn antenna with an aperture of 0.90 in × 0.90 in at a distance of 4.93 cm from the horn. The 1-dB beamwidth of this horn would accommodate five pupae spaced on a 1/2-in center in a triangular grid. Thus waveguide irradiation requires much less source power than free space irradiation at the same power density.

Since the experiments were done in waveguide, it is of interest to consider effects present there which might modify free space irradiation results. One such effect is the excess attenuation obtained in a waveguide partially loaded with a lossy dielectric medium which can exceed that of the same waveguide completely filled with the same material [2]–[4]. This excess loss is due to field concentration effects and could lead to a greater temperature rise in the pupa than anticipated.

The temperature rise due to microwave power absorption was monitored by imbedding a fine copper-constantan thermocouple (0.005-in wire) in the abdomen of sample pupae. The leads were brought out through small lateral channels in the flange of the X-band waveguide section. The leads were perpendicular to the electric field vector to minimize induced currents in the thermocouple. A reference junction was mounted in an identical styrofoam

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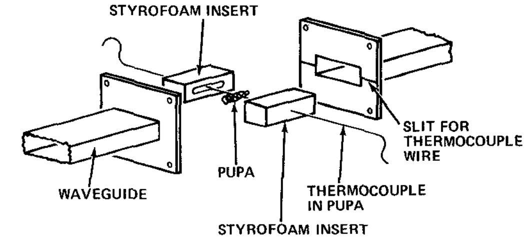


Fig. 1. Arrangement for irradiating pupae in WR-90 waveguide and for thermocouple mounting.

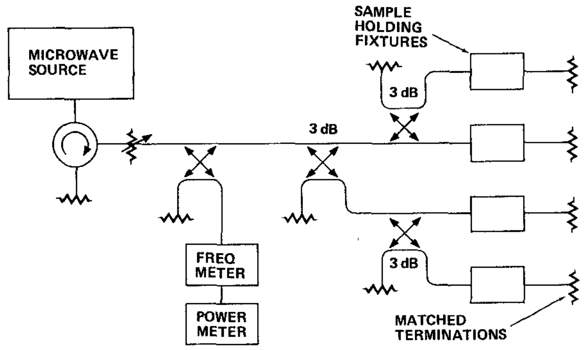


Fig. 2. Microwave circuit for irradiating pupae.

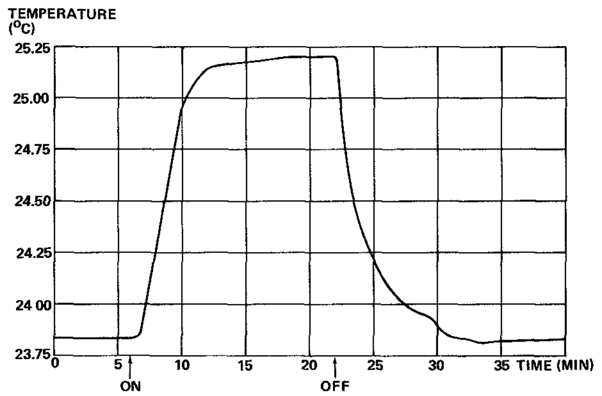


Fig. 3. Internal temperature of pupae as a function of time 20-mW CW microwave irradiation 9.0 GHz.

holder and placed in a length of waveguide receiving no power for a differential measurement to remove fluctuations in room temperature. Other measurements used a reference junction held at 0°C. Irradiation of the thermocouple itself produced no measurable temperature rise.

Fig. 3 shows temperature as a function of time when a pupa is irradiated with 20-mW CW at 9.0 GHz. Its temperature increased by 1.38°C and it reached equilibrium in about 8 min. It relaxed to the ambient temperature about 8 to 9 min after the microwave power was turned off. These results agree with those of Carpenter and Livstone.

In this experiment the posterior portion of the pupa was pointed toward the source. A temperature rise of 1.76°C was obtained with the same pupa oriented with its anterior toward the source. Slightly more power ($\sim$0.5 dB) is absorbed by the pupa when its head is toward the source than when its orientation is reversed.

Pupae were harvested from larvae[1] raised in darkness at room temperature on Special K breakfast food with occasional pieces of potato and apple for moisture. Each day's yield was divided arbitrarily among experimental and three control groups. Some controls were placed directly in numbered vials. Others were mounted in waveguides, as if for irradiation; however, no microwave power was applied. The third group was used as temperature controls. They were placed in a 29°C oven for 2 h. The temperature was 8°C higher than the ambient temperature, rather than the less than 2°C rise produced by the microwave irradiation. While this protocol was less sophisticated than that reported by Carpenter and Livstone, it again demonstrated that the experimental results to be described are not ascribable to slow (8–9-min) changes in the ambient temperature. Transient or localized heating effects have not been ruled out as mechanisms for microwave induced teratological damage. However, no evidence for such effects was observed in our experiments.

[1] Rainbow Mealworms, Compton, Calif.

III. PHENOMENOLOGICAL EXPERIMENTS

A. *20-mW CW Irradiation for 2 h*

B. *Pulsed Fields*

To determine whether teratological damage is a function of average power level or of peak field strength, we conducted experiments with a pulsed high power source operated at a low duty cycle. Fixed width (2.5×10^{-7} s) pulses of 50-W and 5-kW peak power at pulse repetition frequency of 1.6 kHz and 16 Hz, respectively, were used. An average power of 20 mW at 9.0 GHz was thereby maintained. The pupae were mounted in the manner described in the preceding and irradiated for 2 h.

C. *Alignment in Field*

In another experiment based on the consideration that various of the insects' organs, the ganglia of the central nervous system being one example, are distributed along the length of the insect [5] we aligned some pupae parallel to the electric vector of the irradiation field rather than along the waveguide axis. This required construction of an enlarged irradiation chamber consisting of a length of standard X-band waveguide, a tapered section 3/4 λ_g long in which the height increased from 0.400-in to 0.840-in, and a straight section 1/4 λ_g long of 0.840-in height, a mating flange, and the same components in reverse order. A horizontal septum was used to suppress higher order modes. Over the frequency range 8.5–9.5 GHz, the maximum VSWR was 1.37, with a VSWR of 1.12 at 9 GHz. Irradiation was for 2 h at 20-mW CW.

D. *Five-Day-Old Pupae*

Another experiment consisted of irradiating pupae in their fifth day of pupation. This effort was suggested by the work of Van Ummerson [6], [7] which showed that previously differentiated structures in the chick embryo were not marred by microwave irradiation, but only slowed in their development; whereas structures which had not differentiated never did develop. The five-day-old pupae were mounted as described in Section II and irradiated at 20-mW CW for 2 h.

E. *Reduced Power Level*

A fifth phenomenological experiment was to irradiate pupa at 10-mW CW with the duration of irradiation proportionately increased to 4 h to test for a threshold for teratological effects.

F. *Reduced Dosage*

A sixth group of pupae was irradiated at 10-mW CW but for only 2 h to seek the dependence of tetratological damage on the total energy absorbed by the pupa.

The results of these experiments constitute Table I; they are discussed in the following section.

IV. RESULTS AND STATISTICAL ANALYSIS

The categories of morphological damage used both by us and by Carpenter and Livstone are as follows:

- D insect died during pupation;
- $G1$ insect has head and thorax of an adult, but the abdomen of a pupa;
- $G2$ an adult insect, but with rumpled and grossly distorted elytra (wing covering) and perhaps shredded wings;
- $G3$ normal adult except for small discrete holes in the elytra;
- N an apparently normal adult.

Note that the incidence of abnormality increases more than threefold with irradiation while the death rate remains essentially unchanged. The percentage of $G3$ abnormalities shows a particularly dramatic difference between irradiated and control groups. The

TABLE I
INCIDENCE OF TERATOLOGICAL DAMAGE FOR VARIOUS TYPES OF EXPOSURE

Group	D	G1	G2	G3	N	Total
20 mW c.w. 2 hours (Section IIIA)	40 21.7%	25 13.5%	58 31.3%	18 9.7%	44 23.8%	185
Pulsed, 50W peak (Section IIIB)	9 21.4%	7 16.7%	16 38.1%	2 4.8%	8 19%	42
Pulsed 5 kW peak (Section IIIB)	21 22.1%	10 10.5%	30 31.6%	8 8.4%	26 27.4%	95
Aligned 11 to E Field 1 (Section IIIC)	9 24.3%	5 13.5%	12 32.4%	4 10.8%	7 18.9%	37
Five Day Old (Section IIID)	11 21.6%	7 13.7%	11 21.6%	3 5.9%	19 37.2%	51
Reduced Power (Section IIIE)	24 29.3%	14 17.1%	18 21.9%	6 7.3%	20 24.4%	82
Reduced Dosage (Section IIIF)	19 31.1%	5 8.2%	17 27.9%	2 3.3%	18 29.5%	61
Untreated Controls (Section II)	48 20.7%	10 4.3%	23 9.9%	0 0%	151 65.1%	232
Waveguide Controls (Section II)	18 20.8%	4 4.4%	11 12.2%	1 1.1%	56 62.2%	90
Temperature Controls (Section II)	11 20.8%	2 3.8%	7 13.2%	0 0%	33 62.3%	53
Total of Control Groups	77 20.5 %	16 4.3%	41 10.9%	1 0.3%	240 64.0%	375

higher death rate for the reduced power and the reduced dosage groups was not mirrored in data for the controls for those same weeks.

The data were subjected to statistical analysis for the two purposes of delineating differences among the irradiated groups and assessing the likelihood that our results could have arisen by chance. Categories $G1$, $G2$, and $G3$ were combined to avoid undue emphasis on the low rate of occurrence for $G3$.

The classical chi squared test [8] was used in several iterations. First the various control groups were compared with the combined control population. There being no differences significant at the 0.05 level, the control groups were subsequently treated as a single population. Next, the various irradiated groups were compared with the control population. All showed differences significant at the 0.05 level. Hence, it is not likely that the increased incidence of morphological abnormality exhibited by the irradiated groups is due to random fluctuations in the sample population.

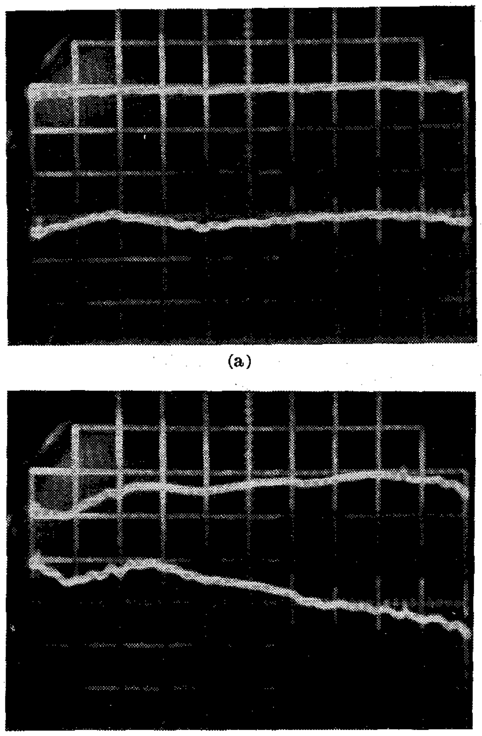
Comparison was made between the group irradiated for 2 h at 20-mW CW and the groups which experienced modified experimental conditions as described in Section III. Only Group F irradiated for 2 h at 10 mW showed significant (0.05) differences. Group D (five-day-old pupa) might show significant differences under a test of greater statistical power, but in this instance failed to do so. Comparison was also made for differences in distribution among the categories $G1$, $G2$, and $G3$; no significant differences were found.

Thus our data do not reveal statistically significant evidence for the dependence of teratological damage on the parameters: a) duty cycle; b) orientation; c) pupa age; or d) irradiation intensity.

V. MICROWAVE MEASUREMENTS

Measurements of return loss and transmission loss from 8–12.4 GHz were made in order to specify the power absorbed by a pupa. A large pupa (0.157 g) mounted as described in Section II showed a return loss of ~13 dB and a transmission loss of 2 dB as seen in Fig. 4. A frequency of 9 GHz was chosen for the CW irradiation experiments. In the absence of special matching, about one third (0.32) of the 20-mW waveguide power is absorbed, constituting a radiometric dosage of 41 mW/g. The same pupa mounted parallel to the electric field in the chamber described in Section III showed a 3-dB return loss and 8-dB transmission loss so that again one third (0.34) of the incident power was absorbed.

In order to obtain an estimate of the macroscopic electrical characteristics of the pupa, several samples were diced and slurried, placed in a short-circuited X-band waveguide section, and held in place by a thin (0.001-in) Mylar sheet. The complex dielectric



(a)

(b)

Fig. 4. Return loss and insertion loss of sample pupa from 8–12.4 GHz. (a) Return loss: vertical scale; 5 dB/div. (b) Insertion loss: vertical scale; 1 dB/div.

constant was measured via the method of von Hippel [9]. Our result at 9.0 GHz and 21°C is

$$\epsilon/\epsilon_0 = 30 - j18.$$

As a check on this technique several solid materials of known dielectric properties and samples of rat liver also were measured with results in reasonable agreement with values in the literature. Tinga and Nelson [10] report a value of 35.9 $-j11.4$ for the rice weevil at 10.2 GHz.

The power density to which the pupa is exposed is not constant along its length, since the pupa is lossy. Also standing waves are present due to discontinuity scattering from the ends of the pupa. Furthermore, because of the high dielectric constant of the pupa and the inhomogeneous loading it provides in the waveguide, the transverse field distribution will likely differ significantly from the empty TE_{10} mode fields.

The voltage standing wave was probed along the length of the pupa by placing a specimen in its styrofoam holder and mounting it in at the center of a slotted line, terminated in a matched load with better than 40-dB return loss. The measured electric field intensity, normalized to the intensity in empty waveguide, is shown in Fig. 5 for a typical pupa, as a function of distance. A standing

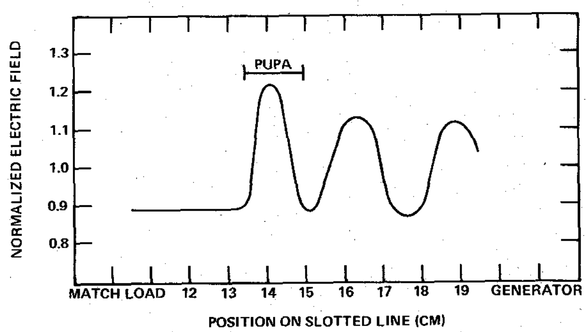


Fig. 5. Normalized electric field intensity at 9 GHz along center line of pupa.

(a) (b) (c) (d)

Fig. 6. Photographs of adult *Tenebrio molitor* showing normal adult and damaged specimens. (a) Normal adult. (b) $G1$. (c) $G2$. (d) $G3$. Note the presence of a hole in the elytra.

wave is noted whose maximum value is 20 percent greater than the corresponding intensity in the empty guide. The apparent normalized guided wavelength, with respect to the empty guide, is $\lambda_g'/\lambda_g \approx 0.72$. The maximum intensity is 415 V/m and occurs midway along the pupa.

It should be noted that many of the $G3$ category defects (small holes in the elytra) in the adult beetles were observed in this region. Photographs of adult beetles exhibiting the various defects are shown in Fig. 6. Notice that the material of the elytra in the $G3$ defect is deformed around the hole, indicating that this is a growth defect rather than a mechanical one.

VI. DISCUSSION

We confirm the finding that microwave radiation at the 10-mW level in WR-90 waveguide causes teratological damage in insects. This damage is not due to handling of the insects by the experimenter nor is it induced by a slow increase in the ambient temperature. However, transient heating effects, even at these low microwave power levels, cannot be ruled out.

The experiments do not show the incidence of damage to be dependent on the orientation of the specimen in the electric field or on the microwave power level. This suggests that the levels used exceed that needed to induce the damage. The incidence of damage does depend on the amount of energy absorbed by the pupa and it may depend on its age when irradiated. For this reason the data of Table I have been combined and presented graphically in Fig. 7. The controls have been lumped to form a single group. Similarly, all one-day-old specimens exposed to a total energy of 72 W·s (Section III-A–C, and E) for the second group. The third group comprises those one-day-old specimens exposed to a total energy of 36 W·s (Section III-F). The figure shows the increased incidence of damage due to irradiation and the dependence on absorbed energy. The increase in the number of dead pupae at the 36-W·s level has not been explained.

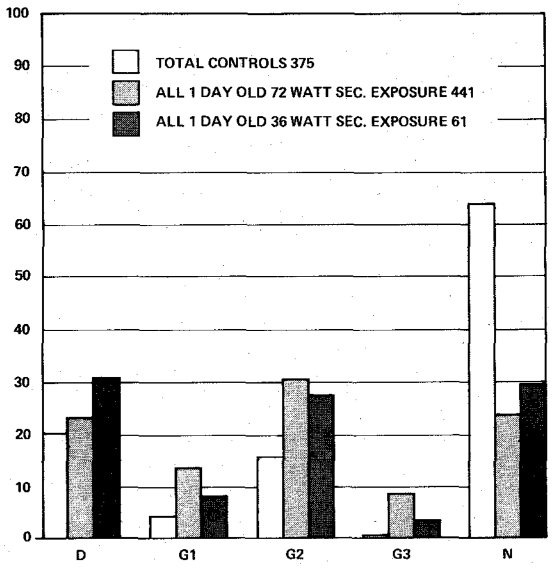


Fig. 7. Effect of 9-GHz radiation in percent of specimens showing given type of damage, compared to the total number exposed.

Experiments conducted to date have not shown the incidence of damage to be dependent on whether the microwave power is pulsed or CW. It must be pointed out, however, that only a small range of pulse repetition frequencies was used in our experiments. Effects with characteristic times shorter than 250-ns pulsewidth or longer than 100-ms repetition period would not have been detected.

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Comparison of Diode Noise Under RF and DC Excitations

Y. LIPKIN AND S. MANIV

***Abstract*—Comparison between the low-frequency noise spectra measurements in microwave diodes under RF and dc excitations are reported. The frequency-dependent noise temperature ratio t measured over a range of low frequencies was approximately 3 dB less with RF excitation than with dc excitation, when the dc bias level was identical in the two cases.**

INTRODUCTION

The work described in this short paper was undertaken in an attempt to determine if a useful empirical relationship could be found relating diode flicker ($1/f$) noise under dc and RF excitation. To estimate the flicker noise, we were faced with the need to make use of flicker noise data on available devices under dc excitation only, which is apparently an industry standard.

A search of the literature indicated that the direct comparison of dc-excited and RF-excited flicker noise at low frequencies had not been investigated and very little work at all on flicker noise measurements under RF excitation [1], [2].

The measurement procedure employed was standard [3]. The results obtained indicate that the noise spectra yielded under dc excitation are somewhat more (3 dB) intense than that yielded

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